SQUID vs. Optically Pumped Magnetometer: a comparison of system performance

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ABSTRACT

Due to their extremely weak intensity, biomagnetic fields are usually detected by means of superconducting interference devices (SQUID) which are currently the most sensitive magnetic sensors available. To reduce construction and running costs, extensive efforts have been dedicated to the development of High-Tc SQUIDs working at liquid nitrogen temperature and suitable for biomagnetic applications, but the results up to now are only partially satisfactory.

Optically pumped magnetometer (OPM) technology, although known for many years, has recently emerged as a promising alternative to SQUIDs, at least for applications with more moderate signal-to-noise requirements. Since OPMs were presented to the biomedical community, a controversy has surrounded their proposed usefulness for different biomagnetic applications. This contribution compares SQUID and OPM methods based on their physical principles: for example by the fact that a SQUID measure the flux through the pick-up-coil area, while the OPM is sensitive to a volume averaged magnetic field component. At the implementation level, the most significant differences between SQUID and OPM are, 1) the absence in OPMs of cryogenic and vacuum parts reducing the gap between source and sensor, and 2) the need for more complex read-out electronics of the OPM .

The intrinsic insensitivity against RF-interference of the OPM reduces the shielding requirements and may ease the introduction of biomagnetic systems into noisy environments. Full technological maturity is by far not yet achieved, thus leaving a large improvement potential, which may eventually allow the OPM to compete with the SQUID even in high-resolution applications.

KEY WORDS

Instrumentation, SQUID-magnetometer, optically pumped magnetometer, biomagnetic field detection.

INTRODUCTION

SQUID magnetometers are to date the most sensitive devices available for the detection of magnetic fields. Their extraordinary sensitivity allows to pick-up extremely weak magnetic signals like the ones associated to the bioelectric currents in living organisms. These signals have different intensities ranging in orders of magnitude from hundreds of pico-Tesla for magnetocardiogram (MCG) down to units or even fractions of femto-Tesla for magnetoneurogram (MNG) and brain-stem associated activities.

To exploit at best the SQUID's sensitivity, several techniques were adopted to deal with the external sources of magnetic and electromagnetic disturbances, which surpass the biomagnetic signals by orders of magnitude. Typically available techniques are passive and/or active shielding, gradiometric design, filters, data-processing algorithms and so on, all having pros and contras especially under the point of view of costs/benefits ratio. Yet SQUIDs are superconducting devices, which need an appropriate cryogenic technique, they are usually operated in liquid helium, and this requires maintenance at regular intervals and at relevant costs. Furthermore a SQUID system cannot be switched-on and operated in minutes like every ECG recorder off-the-shelf, here the start-up time from cool-down to full operation takes several hours. Therefore two ways of operations are usual: 1) if sporadic measurements have to be carried-out, they need to be carefully scheduled and possibly grouped to take the most benefit from cooling-down the sensor for a limited period of time, and then the system warms up, 2) for routine measurements the system is kept cold and running continuously for several months.

All these arguments may have strongly limited over the years the wide spreading of the biomagnetic method. To overcome these problems many efforts have been done in searching for less expensive technologies, both for the sensors and for the noise suppression techniques. The discovery of high-Tc superconductivity in the late 80's looked very promising since it allows one to operate sensors with liquid nitrogen at much lower costs and system complexity, but to date the reliability of HTc-SQUIDs is still an open issue.

Recently it was shown that OPMs can be used for the detection of MCG. The reported noise level was more than one order of magnitude larger than that of currently available SQUIDs, but this is just the beginning of the study and there are good margins for improvements. This paper presents a comparison SQUID vs. OPM and an estimation of chances for the future.

METHODS

A DC-SQUID consists of a superconducting ring interrupted by two identical Josephson junctions. If a biasing current is applied to the ring, under normal conditions the current will equally split into the two junctions and the phase of the wave functions will be the same. An external magnetic flux threading the ring determines a phase shift of the two wave functions, which combined with the flux quantization phenomenon leads to the well known periodic flux-to-voltage transfer function, whose period is equal to a flux quantum ϕ_0 of $2 \cdot 10^{-7}$ Gauss cm^2. Beside the extra-ordinary sensitivity, this behavior has the disadvantages of nonlinearity and limited dynamic range. Therefore the SQUID is driven by suitable feedback-electronics that keeps the working point of the SQUID locked at a fixed value (Flux-Locked-Loop) [Clarke, 1969], [Koch, 1989]. Such a SQUID magnetometer shows an excellent linearity over five to six orders of magnitude and the minimum detectable flux can be in the range of $\mu\phi_0$

A typical biomagnetic SQUID-based system consists of: sensor array, cryogenic probe and readout electronics at room temperature. The cryogenic probe is required because the SQUID operates in liquid Helium at the temperature of 4.2 K, in a thermally shielded enclosure (dewar). The outstanding features of these instruments include a wide dynamic range (at least 100 dB), a wide bandwidth from DC up to a few tens of kHz at a noise level in the white region (Nyquist), ranging from a guaranteed values below 10 fT/√Hz in commercial systems, down to 2 fT/√Hz for the best research devices [Drung, 1995].

In an OPM a vapor of paramagnetic atoms sealed in a glass cell (Fig. 1 b) is used to detect magnetic fields via the induced Larmor precession of a long-lived spin polarization [Alexandrov, 1993]. Its principle of operation is based on a resonant circularly polarized laser beam, which creates spin polarization in the atomic vapour via optical pumping. The magnetization precesses around the external magnetic field B_0 at the Larmor frequency

$?_L$ which is proportional to the modulus of B_0. A reference phase is imposed by a magnetic field B_1 (radio-frequency) co-rotating with the spins around B_0 at frequency $?_{rf}$. The driven magnetization induces an oscillating component of magnetization on the laser-beam axis, which modifies the optical absorption properties of the medium, which is detected by monitoring, with a photodiode and a lock-in amplifier synchronized to $?_{rf}$, the beam power transmitted through the sample. The signal shows a resonant behavior when $?_{rf}$ approaches the Larmor frequency. The sensitivity of the *Mx* magnetometer to external magnetic fields varies as sin 2?, where ? is the angle between the laser-beam direction and the magnetic field and has thus an optimum sensitivity for ? = 45. Therefore the bias field B_0 = 5 µT is best applied to the sensor at ? = 45° (45° geometry, see Fig. 1.b). The photocurrent is analyzed by a lock-in amplifier referenced by the radio frequency $?_{rf}$. When operated in this *Mx* configuration the device acts as a scalar magnetometer whose signal is a function of $|B_0|$. As the MCG-induced field changes $\boldsymbol{B}$ are much smaller than the offset field $\boldsymbol{B}_0$ applied in the *z* direction, the signal changes of the magnetometer will be (to first order) proportional to *Bz* only; this makes the device act as an effective vector magnetometer. Active noise suppression, based on a first-order gradiometric design, can be arranged with two identical magnetometers.

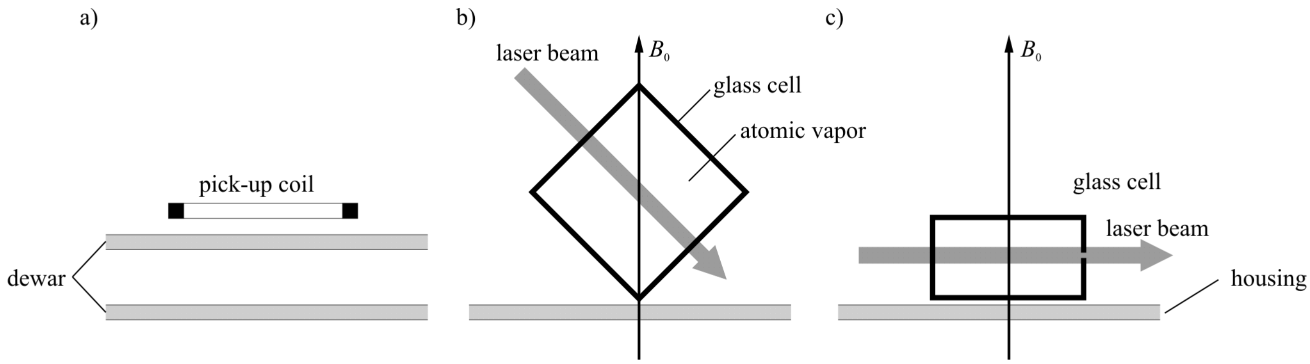

Figure 1 a) Geometry of a SQUID system. b) 45° geometry of the optical Mx magnetometer. c) Flat geometry of future optical magnetometers.

The typical intrinsic sensitivity achieved with a cylindrical glass cell (diameter 20 mm, length 20mm), filled with a droplet of caesium metal and a buffer gas mixture, is around 100 fT/√Hz [Bison, 2003]. Recently the system could be optimized to operate with an intrinsic sensitivity of 63 fT/√Hz and a detection bandwidth of 140 Hz. Simple model calculations comparing the signals measured by SQUID and by OPM assuming a dipolar source shows that the absence of a dewar, i.e., a smaller distance between source and sensor, can partially compensate for the smaller sensitivity of the OPM. The effect is of course small for deep lying sources (an improvement of the sensitivity of only few percent) but can be relevant for sources near the surface (up to 40% for a depth of 30 mm). Future designs of optical magnetometers, based on a slightly different magnetooptical technique, will increase this effect significantly by using flat geometriey (Fig. 1 c).

DISCUSSION

The experience gained until now from the recording of MCG data in a weakly shielded or unshielded environment is showing that the intrinsic noise limits of the measurement systems (dominated in SQUID systems by the environmental noise) do not differ by orders of magnitude, but only by a factor 3 or 4. There is founded expectation that in the near future that gap can be reduced perhaps to a factor of 2. The advantage of the OPM based system, being free of cryogenics and practically using standard electronic equipment is clearly in favor of a broad clinical application of the OPM technique. The most important step will be to demonstrate that in the clinical routine there will be accepted applications where the slightly reduced sensitivity is not a decisive drawback.

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